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Depinning fields of a magnetic domain wall from asymmetric notches

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Depinning fields of a magnetic domain wall (DW) from asymmetric notches artificially introduced into submicron magnetic wires were investigated by utilizing the giant magnetoresistance effect. It was found that the depinning field from the asymmetric notch depends on the propagation direction of the DW. The asymmetric notch works as an asymmetric potential barrier against the DW propagation. The depinning field increases with increasing slope of the asymmetric notch. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2167327]

Magnetization processes of artificial ferromagnetic structures such as wires, dots, and particles with submicron or nanometer size have been widely researched.[1–8] Such a research is of great significance for designing magnetic devices such as hard disk drive, magnetic solid memory, and other spintronics devices. Magnetic domain structure and magnetization reversal in these ferromagnetic structures can be controlled by modifying their shapes due to the shape magnetic anisotropy. In a previous report on depinning of a magnetic domain wall (DW) in a submicron magnetic wire with asymmetric notches, it was found that the depinning field of the DW from the asymmetric notch depends on the DW propagation direction.[7] This phenomenon could be described as a "magnetic ratchet effect." A similar effect was found in the experiment on submicron magnetic wires with a triangular structure using a magneto-optical Kerr effect.[8] In this article, we present a study on the depinning fields of the DW from various asymmetric notches in magnetic wires.

Figure 1 shows a schematic illustration of a top view of the sample. A magnetic wire has a trilayered structure consisting of $Ni_{81}Fe_{19}$(5 nm)/Cu(20 nm)/$Ni_{81}Fe_{19}$(20 nm), in which the propagation of the DW in the NiFe(20 nm) layer can be detected by utilizing the giant magnetoresistance (GMR) effect.[1,2] The magnetic wire has four notches with triangular asymmetric shape. We prepared three kinds of samples in which the width of the widest part along the magnetic wire (w) are 400, 450, and 500 nm. Furthermore, the sample has two narrow Cu wires crossing both ends of the magnetic wire. These Cu wires are electrically insulated from the magnetic wire by SiO_2 layers of 100 nm thickness. A flow of a pulsed electric current in each Cu wire at the left or the right end of the magnetic wire can generate local magnetic fields, H_L or H_R, respectively. $H_L(H_R)$ can trigger the nucleation of a DW at the left (right) end of the magnetic wire. Thus, the propagation direction of the DW can be controlled by $H_L(H_R)$.

In order to investigate the relation between the depinning field and the shape of the asymmetric notch, we performed magnetoresistance (MR) measurements described in Ref. 7 for the three kinds of samples with different w. Figure 2(a) shows a typical result of the MR measurement for the sample with asymmetric notches (w=500 nm), which is the same as in Ref. 7. The increase in resistance at H_{ext}=10 Oe originates from the magnetization reversal of the NiFe(5 nm) layer, while the decrease in resistance at H_{ext}=155 Oe corresponds to the magnetization reversal of the NiFe(20 nm) layer. In the case of the magnetization reversal of the NiFe(20 nm) layer, we did not find any measured point during the magnetization reversal, indicating that the magnetic DW was not pinned by asymmetric notches during the magnetization reversal of the NiFe(20 nm) layer because of its large nucleation field. In order to nucleate a DW in the NiFe(20 nm) layer at smaller H_{ext}, we utilized the method of generating a pulsed local magnetic field at the end of the magnetic wire. Figure 2(b) shows the result of the DW injection into the NiFe(20 nm) layer of the magnetic wire by H_L. The measurement procedure is the same as that of the measurement shown in Fig. 2(a), except for applying H_L when H_{ext}=40 Oe. The magnitude and duration of the pulsed H_L were 200 Oe and 100 ns, respectively. The resistance abruptly decreased after the application of H_L and stayed at a value between the largest and the smallest values. The value of the resistance indicates that a DW injected from the left by H_L was pinned at the leftmost notch. By increasing H_{ext} after the injection of the DW, the resistance decreased to the smallest value at 83 Oe, which indicates that the DW propagated to the right end of the wire

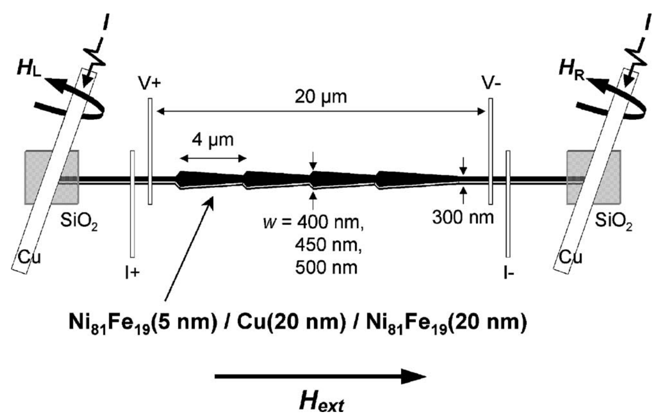

FIG. 1. Schematic illustration of a top view of the sample. A magnetic wire with asymmetric notches has a trilayered structure consisting of $Ni_{81}Fe_{19}$(5 nm)/Cu(20 nm)/$Ni_{81}Fe_{19}$(20 nm). A flow of an electric current in the Cu wire crossing both ends of the magnetic wire generates a local magnetic field (H_L,H_R), which injects a magnetic DW.

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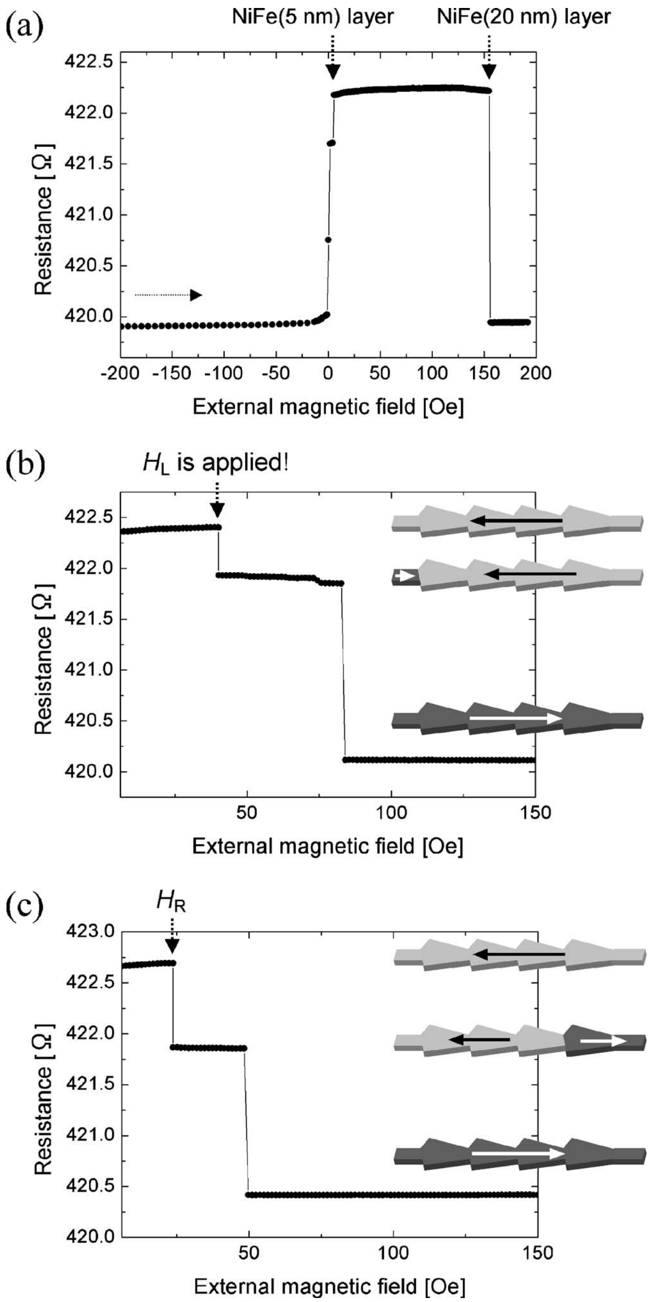

FIG. 2. Resistance change of the trilayered magnetic wire with asymmetric notches (w=500 nm) as a function of the external magnetic field. (a) Typical MR curve of the trilayered system. (b) The magnetic DW was injected into the NiFe(20 nm) layer from the left end of the magnetic wire by the pulsed H_L. Magnetic domain structures in the NiFe(20 nm) layer inferred from the resistance change are schematically shown. (c) The DW was injected from the right end of the wire by the pulsed H_R.

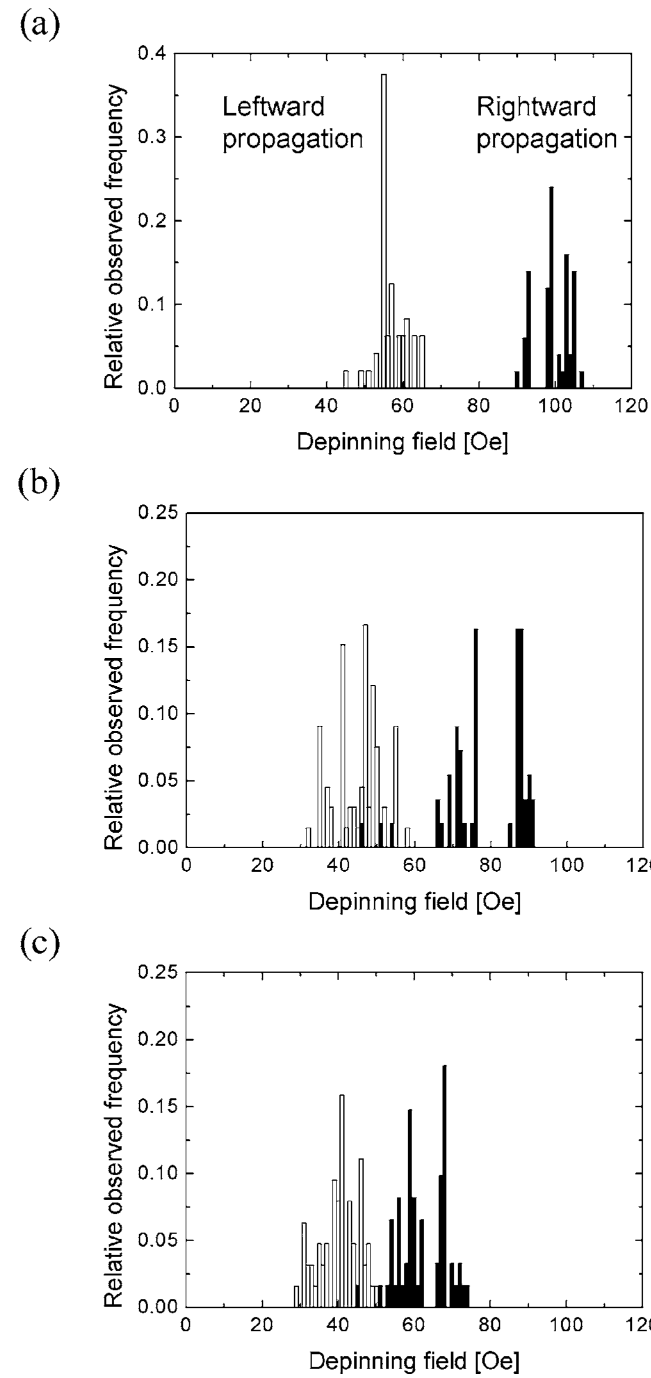

FIG. 3. Distributions of the depinning fields of the DW for the NiFe(20 nm) layer from asymmetric notches: (a) w=400 nm, (b) w=450 nm, and (c) w=500 nm.

through the asymmetric notches. Thus, the depinning field for the rightward propagation of the DW can be determined to be 83 Oe. On the other hand, the depinning field for the leftward propagation of the DW can be determined from the result shown in Fig. 2(c), which shows the MR measurement when the DW was injected from the right end of the wire by H_R. In this case, the depinning field was 48 Oe. Thus, the depinning field for the rightward propagation is much larger than that for the leftward propagation. In these results, the values of the depinning fields differ by a few oersteds from those of the identical sample in Ref. 7. This is because the depinning fields have an intrinsic distribution due to the thermal fluctuation.

Figures 3(a)–3(c) show the distributions of the depinning field of the DW from the asymmetric notch with w=400, 450, and 500 nm. The results of Fig. 3 were obtained by repeating the MR measurements 50 times for each propagation direction of the DW. As shown in Fig. 3, there is a significant gap (lack of data points) in the center of the distribution for the rightward propagation. This could be due to the minute shape defect of each notch and the difference of

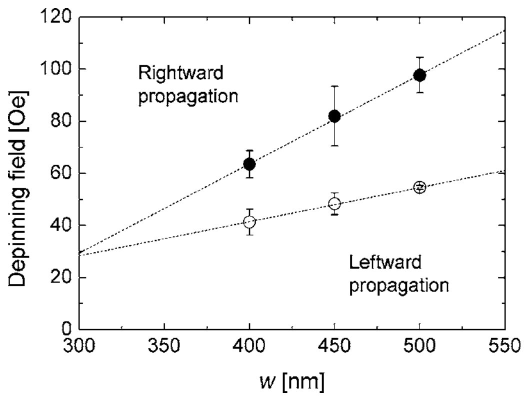

FIG. 4. Relation between the depinning field and the width of the widest part along the magnetic wire (w). The black and white dots show the mean values of depinning fields for the rightward and leftward propagations of the DW, respectively.

the internal structure of the DW at each measurement. By fitting the Gaussian distribution function to the results of Fig. 3, the mean value of the depinning field was obtained. The relation between the depinning field and w is plotted in Fig. 4. The black and white dots show the mean values of the depinning field for the rightward and leftward propagations, respectively. The error bars in Fig. 4 show the full width at half maximum of the Gaussian fits of the distribution of the depinning fields. The depinning fields for both propagation directions increase with increasing w. Thus, the notch with the steeper slope has the larger depinning field.

The interpretation as to why the depinning field depends on the slope of the asymmetric notch is the following. Since the DW energy is proportional to its area, the DW at a wider position along the wire has a larger energy. This change in the DW energy along the wire produces the pinning potential for the DW. Thus, the force to move the DW against the potential, that is to say, the depinning field, increases with increasing slope of the asymmetric notch.

In conclusion, the depinning fields of a magnetic DW from asymmetric notches in a submicron magnetic wire were investigated by utilizing the GMR effect. For all samples used in this study, the depinning field depends on the propagation direction of the DW. The asymmetric notch with the wider w has the larger depinning field. The height and slope of the potential barrier produced by the asymmetric notch can be controlled by w.

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